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Prospects of apoptotic cell-based therapies for transplantation and inflammatory diseases

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ABSTRACT/SUMMARY:

Apoptotic cell removal or interactions of early stage apoptotic cells with immune cells are associated with an immunomodulatory microenvironment that can be harnessed to exert therapeutic effects. While the involved immune mechanisms are still being deciphered, apoptotic cell infusion has been tested in different experimental models where inflammation is deregulated. This includes: chronic and acute inflammatory disorders such as arthritis, contact hypersensitivity, or acute myocardial infarction. Apoptotic cell infusion has also been used in transplantation settings to prevent or treat acute and chronic rejection, as well as to limit acute graft-versus-host disease associated with allogeneic hematopoietic cell transplantation. Here, we review the mechanisms involved in apoptotic cell-induced immunomodulation and data obtained in preclinical models of transplantation and inflammatory diseases.

KEYWORDS: apoptotic cells; inflammation; transplantation; macrophages; dendritic cells; regulatory T cells; immunotherapy; cell therapy; arthritis; tolerance

Drugs and biotherapies are not devoid of side effects and improvements in patient treatment are needed. Indeed, biological agents, such as anti-TNF, have significantly improved the treatment of inflammatory chronic diseases, such as rheumatoid arthritis (RA). However, 30 to 40% of RA patients are considered to be refractory or contraindicated to these agents. In solid organ transplantation settings, acute graft rejection is now significantly controlled by immunosuppressive drugs. In contrast, the benefits of such immunosuppressive drugs on chronic rejection and overall long-term graft survival are still uncertain. Allogeneic hematopoietic cell transplantation is an efficient immunotherapy to cure leukemia. However, this approach is associated with major life-threatening complications, notably graft-versus-host disease (GvHD) which occurs in 30 to 80% of allografted patients. Cell-based therapies are new alternative therapeutic strategies that can be used to limit, or even, control all these pathologies with limited toxic effects. More than ten years ago, we propose to use intravenous (iv) early apoptotic cell infusion as an alternative cell-based therapeutic approach in allogeneic hematopoietic cell transplantation, initially conceptually [1], and then experimentally [2]. In this review, we will introduce immunomodulatory mechanisms associated with early apoptotic cells. Then, we will report and discuss data obtained in preclinical experimental models, before proposing future perspectives for such therapeutic approach.

Immunomodulatory properties associated with early apoptotic cells

- An immunosuppressive/anti-inflammatory microenvironment created by the apoptotic cell death

Apoptosis is a cell death mechanism occurring in different physiological situations, including development, or during normal cell turn over with elimination of unwanted or undesirable cells. For instance, more than half of the cells are eliminated by apoptosis in the mammalian brain during development[3]. More than one hundred billion of neutrophils die daily by apoptosis[3]. Elimination of apoptotic neutrophils by macrophages following tissue injury—a process called efferocytosis[4]—is critical for the resolution of inflammation, as well as initiation of tissue repair[5]. In all these situations, apoptotic cells are quickly removed after apoptosis has been triggered [6]. This

elimination takes place before the apoptotic cells become completely dislocated [6], and is estimated to occur less than 3 hours after the apoptotic signal initiation [7]. This suggests initially that apoptotic cell death is a silent immune mechanism [8, 9]. Apoptotic cells are preferentially uptaken by professional phagocytes, such as macrophages [10-16], microglia in the brain [17-20], and/or some dendritic cells (DC) subsets [14, 15, 21-23] that move to the sites where cells die in response to specific signals, called “find-me” signals [24] (Figure 1). In general, these “find-me” signals correspond to the translocation of intracellular structures to the apoptotic-cell surface that engage with phagocytes via their multiple cognate receptors (Figure 1). Then, professional phagocytes can release after apoptotic cell removal immunosuppressive cytokines that neutralize subsequent immune responses (Figure 2). Thus, both macrophages [25, 26], microglia [27] and human monocyte-derived DC [28]—a model for inflammatory conventional DC [29]—have been reported to produce interleukin (IL)-10 after apoptotic cell uptake. Interactions of apoptotic cells with monocytes induce IL-10 secretion after lipopolysaccharide (LPS) stimulation [30]. Secretion of TGF- β after apoptotic cell removal by macrophages [11, 31], microglia [27] or conventional DC [31] has also been described. Secretion of these anti-inflammatory cytokines can occur spontaneously after apoptotic cell encounter or is observed after stimulation with Danger signals mimicked *in vitro* by TLR ligands (LPS or zymosan, for TLR4 and TLR2, respectively) (Table 1). Regulatory factors other than immunosuppressive cytokines, such as retinoid acid [32], prostaglandin-E2 (PGE2) [11, 27], enhanced tryptophan catabolism via stimulation of indoleamine 2,3-dioxygenase (IDO) enzymatic activity [33, 34], and/or specialized pro-resolving lipid mediators (e.g., resolvins) [35], are also produced by professional phagocytes eliminating apoptotic cells (Figure 2). Thus, immunosuppressive cytokine-independent mechanisms induced by apoptotic cells have been also reported [33-38]. For instance, nitric oxide (NO) is spontaneously produced by mouse macrophages after interactions with early apoptotic cells [37, 38]. This prevents the release of MIP-2, the murine homolog of IL-8, which plays a role in neutrophil recruitment [38]. Synthesis of NO after apoptotic cell removal by murine macrophages inhibits also the production of the chemokine KC [37]. Moreover, uptake of apoptotic cells by professional phagocytes

is associated with a decreased capacity to produce pro-inflammatory cytokines, including:TNF, IL-1 β , IL-6, IL-8,GM-CSF, IL-12 or IL-23[11, 20, 23, 28, 31, 39-41], or inflammatory factors, such as,reactive oxygen species (Figure 2). Again, as observed for anti-inflammatory cytokines, decrease of pro-inflammatory factor synthesis can occur spontaneously after apoptotic cell interactions in pathological situations where pro-inflammatory cytokine production is exacerbated. Prior apoptotic cell removal prevents also *ex vivo*pro-inflammatory cytokine secretion by TLR stimulation (Table 1).A decrease of pro-inflammatory cytokine secretion after apoptotic cell exposure can be a direct effect on pro-inflammatory cytokine genes, independent of IL-10 and TGF- β [39, 41].Thus, the immunosuppressive microenvironment created by apoptotic cells themselves[42-44]is transiently amplified by professional phagocytes after apoptotic cell removal.

- A possible transfer of the immunomodulatory message to adaptive immune cells by antigen-presenting cells

The contact of conventional DC with apoptotic cells blocks their ability to mature and produce inflammatory cytokines, while their homing capacity might be stimulated. Hence, conventional DC acquire the expression of CCR7 [45, 46] –that in response to CCL19 and CCL21 gradients– guides DC to the draining lymph nodes. In the draining lymph nodes, conventional DC exposed to apoptotic cells can interact with naive T cells and deliver a “tolerogenic” signal favoring T cell commitment into a regulatory phenotype, such as peripherally-derived Foxp3⁺ CD4⁺ regulatory T cells (abbreviated pTreg according to a recent nomenclature [please refer to Abbas AK et al., Nat Immunol., 2013]) or IL-10-producing Tr1 cells[14, 31, 36, 47, 48]. Macrophages after apoptotic cell removal may also possess the ability to migrate to draining lymph nodes [5, 49]. However, this function may be restricted to “satiated” macrophages (*i.e.*, stuffed macrophages with apoptotic cells) [50]. Since macrophages usually degrade completely engulfed antigens due to their contents in proteolytic enzymes [51], no antigen presentation to T cells is considered to occur[52]. However, one may imagine that emigrating macrophages release immunosuppressive cytokines in the draining lymph

nodes leading to a transient local non-specific immunosuppression which may affect DC/T cell/B cell interactions.

■ A focus on the role of professional phagocytes in apoptotic cell-induced immunomodulation

Macrophages and DC represent both heterogeneous cell subsets with each cell subset dedicated to distinct functional properties. Significant improvements have been recently performed on the functional characterization and the ontogeny of macrophage [53] and conventional DC subsets [54]. Among these new findings [53, 54], some may impact on apoptotic cell removal and its functional consequences. Concerning macrophages, characterization of M1/M2 phenotypes, macrophage origin (tissue-resident *versus* blood monocyte-derived macrophages) and macrophage location may influence apoptotic cell elimination with some macrophages more dedicated to this job. This includes, for instance, the following subsets: IL-10-producing alternatively activated M2 macrophages [55], or glucocorticoid and M-CSF, or IL-10 and M-CSF-derived M2 macrophages [16]. Furthermore, tissue resident macrophages may prevent apoptotic cell removal by inflammatory monocyte-derived macrophages in a 12/15-lipoxygenase-dependent manner [56]. Marginal zone macrophages of the spleen are specialized in the uptake of blood-borne apoptotic leukocytes [12, 13]. In addition, marginal zone macrophages can secrete after apoptotic cell removal CCL22 to recruit specifically Treg [57]. Recent data describe the relationship between dedicated antigen-presenting cell (APC) subsets and the induction of pTreg, one of the main mechanisms involved in peripheral tolerance. This is true for macrophage subsets in the lung [58] or the intestine [59], as well as for DC subsets both in Human [52, 60] and mouse [61]. The recent characterization of migratory *versus* lymphoid-resident conventional DC can be useful in the future to better define the role of distinct APC subsets in apoptotic cell-induced tolerance and to target preferentially tolerogenic APC. While migratory conventional DC take up antigens from peripheral tissues, lymphoid-resident DC capture antigens from the blood or the lymph. Thus, blood-borne apoptotic leukocytes are rather eliminated by marginal zone CD8 α^+ conventional DC [23, 62]. In contrast, migratory DC arise in peripheral tissues and then migrate into the lymph nodes. In steady state (*i.e.*,

in absence of Danger signals or an ongoing inflammatory response), peripheral tolerance related to pTreg induction is rather induced by migratory conventional DC [61, 63] –as observed in the skin [61, 64], the lung [61], and the gut [65]– than lymphoid-resident CD8⁺ DC, as initially thought [66]. In rats, a conventional DC subset dedicated to transport continually apoptotic cell-derived materials to T cell areas of the draining lymph nodes (*i.e.*, mesenteric lymph nodes) has been described in the intestine [21]. Mouse migratory CD103⁺ conventional DC acquire apoptotic cell-derived antigens in the lung under steady state and present them to T cells in the draining lymph nodes [67]. In addition to peripheral tolerance, central tolerance to antigens from cells dying in the periphery can also be achieved, since peripheral conventional DC [68] as well as PDC [69] can transport antigens from the periphery to the thymus and may participate in antigen-reactive thymocyte deletion. Understanding the fine mechanism responsible for tolerance to apoptotic cell-derived antigens and more precisely the identification of APC subsets can be harnessed to favor or restore tolerance in transplantation settings or during inflammatory/autoimmune disorders, respectively.

■ A neglected/an emerging role of non-professional phagocytes?

In addition to professional phagocytes, non-professional phagocytes (*i.e.*, neighboring cells) can also uptake apoptotic cells (Table 2). The process of apoptotic cell removal by *amateur* phagocytes is usually slower [70-72], requires apoptotic cells in a more advanced stages [70] and is limited to subcellular fragments (*i.e.*, a smaller “prey”) rather than whole dying cells [71, 73]. Secondary necrosis due to delayed or impaired apoptotic cell removal leads to the release of toxic intracellular compounds that corresponds to Danger signals, named damage-associated molecular patterns (DAMP) [74]. These DAMP activates APC that, in turn, initiate efficient T cell responses through Th1, Th2 or Th17 differentiation profile. Moreover, in certain conditions, pro-inflammatory chemokines (e.g., IL-8, MCP-1/CCL2 and RANTES/CCL5) are released by these non-professional phagocytes [75, 76], leading to inflammatory cell recruitment. On the other hand, in certain tissues where professional phagocytes have limited access in steady state (e.g., the retina or the kidney), neighbor *amateur* phagocytes participate efficiently to the quiet elimination (*i.e.*, without

inflammation) of apoptotic cells[77, 78]. Thus, depending on the cells involved in apoptotic cell removal and on the speed/kinetics of this removal, apoptotic cells may block or initiate immune responses. One has to evoke the status of another APC that interacts with T cells: plasmacytoid dendritic cells (PDC), a particular DC subset that differ from conventional DC (for review [79]). No doubt exists that PDC can uptake dying cell materials[80, 81], as almost each cell type seems to be able to do it (Table 2). It remains to be determined whether PDC correspond to real professional or non-professional phagocytes. Several arguments suggest that PDC are non-professional phagocytes, including: *i*) delayed apoptotic cell elimination[82], *ii*) subcellular fragment uptake as attested by endocytosis of apoptotic cell-derived membrane microparticles or apoptotic bodies[82, 83] but not whole apoptotic cells [84, 85], *iii*) the release of pro-inflammatory cytokines (e.g., IFN- α , IL-6)[83, 86]. However, despite limited capacity to uptake apoptotic cells, PDC may play a role in apoptotic cell-induced immunomodulation by interacting with other immune cells: macrophage and pTreg[84].

■ Receptors and soluble factors involved in apoptotic cell removal

Finally, the capacity to eliminate apoptotic cells and to be a professional or an *amateur* phagocyte may depend on engaged receptors involved in apoptotic cell uptake, as well as the possibility to secrete soluble proteins enhancing apoptotic cell removal (e.g., milk fat globule EGF factor 8 protein [MFG-E8] called also lactadherin[87], growth arrest-specific 6 [Gas6][88], or defense collagens including the complement component C1q, mannose-binding lectin, pulmonary surfactant protein A and D or adiponectin[89]). As stated before, apoptotic cell removal implicates cognate receptors on phagocytes and specific ligands displayed by apoptotic cells. These ligands are called either “eat-me” signals or apoptotic cell-associated molecular pattern (ACAMP) in reference to pathogen-associated molecular pattern (PAMP) expressed by pathogens (Figure 1). Interactions between phagocytes and apoptotic cells implicate multiple ligand/receptor pairs. Identification and characterization of these receptors and their ligands is an active research field (for review [90]). Whether the preferential implication of a particular receptor or of a set of receptors in apoptotic cell removal is associated with a particular function of phagocytes remains to be determined. Nevertheless, recognition of

phosphatidylserines –expressed early after apoptosis– is associated with anti-inflammatory cytokine release[11, 91]. Preventing phosphatidylserine recognition on apoptotic cells shifts the immune response from tolerance to immunogenicity[92, 93]. The same observation has been performed with the genetic invalidation of the Mer tyrosine kinase (Mertk)[94] –a phagocyte receptor that binds the soluble phosphatidylserine ligand, Gas6–, or of MFG-E8 soluble factor [95]–that links phosphatidylserines expressed by apoptotic cells to phagocyte $\alpha_v\beta_3/\beta_5$ integrins. Moreover, in the absence of functional complement protein C1q in mouse models or in patients, failure to remove apoptotic cells is associated with lupus-like systemic autoimmune diseases[89]. C1q deficiency is an illustrative example for the major role of soluble factors in apoptotic cell-induced immunomodulation. Indeed, C1q participates in the classical complement-dependent engulfment of apoptotic cells [23, 96, 97], but is also able to bind directly phosphatidylserine residues of these dying cells [98] and to stimulate the expression of Mertk and Gas6 that, in turn, increase the capacity of macrophages to remove apoptotic cells [99]. Furthermore, C1q affects macrophage polarization during apoptotic cell uptake by inhibiting IL-1 β secretion [100]. Finally, the classical complement-dependent elimination of apoptotic cells occurs mainly through IgM opsonisation[89]. This explains why IgM may be required for modulation of immune responses by apoptotic cells [36]. A better characterization of these receptor/ligand interactions will permit in the future to optimize apoptotic cell-based therapies and maybe to treat autoimmune diseases associated with a defect of apoptotic cell removal, such as lupus.

■ Toward the use of the immunomodulatory properties of apoptotic cells in clinical settings

In conclusion, several factors influence the immune response following apoptotic cell removal (Figures 1 and 2). This includes: *i*) which cell type dies[35], *ii*) the phagocyte cell type (macrophages *versus* DC *versus* non-professional phagocytes) which can be linked to the site where the cell dies, *iii*) the settings in which the cell dies (that is associated or not with Danger signals, either DAMP, or PAMP), *iv*) the factors released by phagocytes and apoptotic cells, and *v*) the cause of cell death. Indeed, apoptosis was initially defined morphologically[101], but different biochemical pathways in

response to different apoptotic stimuli lead to diverse apoptotic cell deaths with distinct immune consequences (tolerance *versus* immunogenicity)(for review on molecular definitions of apoptotic cell death, please refer to [102]; please also refer to a review dealing with immunogenic and tolerogenic cell death [103]). In a recent review [104], the 5 factors evoked above were called the 5 Ws of dying cells (for: Who, Where, Why, What and When). This enables to predict the immunological outcome of apoptotic cell death. Considering apoptotic cell-based therapy to limit inflammation and control undesirable immune responses, the following criteria have been selected: early apoptotic mononuclear cells (*i.e.*, mainly lymphocytes), intravenous infusion to target preferentially splenic professional phagocytes (marginal zone DC and/or macrophages that deal each day with billions of dying leukocytes), and induction of tolerogenic apoptosis (see next paragraph).

Preclinical data using early apoptotic cell infusion in experimental models

As discussed in the first part of this review, apoptotic cells are able to modulate the functions of several immune cells, including: macrophages, DC, NK cells, or CD4⁺ T cells. The functions of these cells are deregulated in several inflammatory or autoimmune diseases. This is the case, for instance, of deregulated inflammatory cytokine secretion in sepsis or in RA. Based on their immunomodulatory or transient immunosuppressive properties described above, apoptotic cell administration has been performed in different experimental models of inflammatory and/or immune disorders (Table 3). From these studies, it is possible to better understand how apoptotic cells interact with the immune system, but also to propose the design of future clinical approaches. In this part of the review, we will analyze the different preclinical studies (Table 3) to select critical parameters to exert therapeutic effects, or in the contrary, to exclude factors that lead to no or opposite effects. Most of the studies report the prevention of the disease; that means that, apoptotic cells were infused at the triggering of the disease (*i.e.*, at immunization with auto-antigens, or at time of transplantation) or before the disease occurred. This is true for: type 1 diabetes in NOD mice [47], experimental autoimmune encephalomyelitis (EAE) [12, 62, 105], arthritis [36, 106, 107], fulminant hepatitis [108], contact hypersensitivity [109-111], acute and chronic graft rejection [85, 112-114], hematopoietic cell

engraftment[2, 14, 84, 115, 116], acute graft-versus-host (GvHD) disease [14]and reduction of infarction size after acute myocardial infarction[117, 118]. Thus, it is difficult to transpose this in the clinical setting where, in general, the disease is already present when a therapeutic solution has to be found. Nevertheless, one may propose that apoptotic cell infusion can be useful in disease prevention associated with a high risk of morbidity/mortality, such as GvHD (please refer to a recent review on the use of apoptotic cells in allogeneic hematopoietic cell transplantation [119]), a high risk of graft rejectionor in prevention of diabetes in the pre-diabetic stage. The use of apoptotic cell infusion in the prevention of complications associated with transplantation (*i.e.*, graft rejection or GvHD) is conceivable, since, in general, the transplantation process is scheduled, and so, apoptotic cell infusion can be performed before or at time of the transplantation, before the complications occurs. However, it is difficult to apply to cadaveric solid organ transplantation where the transplantation procedure is not predictable. Moreover, apoptotic cell administration has also been tested in experimental models to treat ongoing active diseases (as in the “real life”), such as acute heart graft rejection[114], chronic GvHD(our unpublished data) or sepsis[91, 120]. This latter pathology is interesting, since administration during the disease protects mice from sepsis-induced death[91, 120],while infusion 5 days before sepsis worsens mice survival, possibly by decreasing the capacity to secrete IFN- γ [121]. Thus, this opens the way to use apoptotic cell administration to cure ongoing diseases, such as acute graft rejection or chronic GvHD without specific side effects (e.g., auto-antibody production)[122].

How clinical trials using apoptotic cells should be designed? In other words, we will now address from the experimental data the critical parameters for the future clinical studies, namely: *i*) the route of administration; *ii*) the number (schedule) of administration; *iii*) the adequate apoptotic cell typeto be used and the apoptotic signal. Most of the studies (91%, 20 out of 22) used the intravenous (iv) route of administration (Table 3). Consequently, the spleen and its marginal zone APC (lymphoid resident CD8 α^+ DC[62, 85, 114], B cells [105, 106]or macrophages[12, 14, 84]) are critical for the modulation of the immune responses, since the spleen is the main filter for blood-borne apoptotic

cells[123]. In contrast, 4 studies reported apoptotic cell infusion either intra-peritoneally (ip)[106, 107], intra-tracheally[91] or intra-myocardially[118]. Some studies compared these routes of administration and iv route; no difference was observed[106, 118]. These particular routes were evaluated, since the diseases were induced through the same routes[91, 107]. Thus, this may theoretically present the advantage of targeting the affected organ (e.g., the myocardium[118], the lung or the peritoneum[91]) without generating a systemic effect. Apoptotic cell-based therapies can be useful to treat systemic diseases, and in this case, the iv route has to be preferred. On the other hand, this approach can be used in local diseases by injecting closed to the affected organs/tissues. The infused apoptotic cell number and the schedule of infusion are relatively homogeneous among the different studies: 10^5 to 5×10^7 in mice[2, 12, 14, 36, 47, 62, 84, 85, 91, 105, 106, 108-116, 120, 121], or 8×10^6 to 10^8 in rats[107, 117, 118]. In general, only one infusion was performed (86%, 18 out of 21). Prevention of type 1 diabetes [47] and arthritis [36, 106] may require repeated infusion. Thus, the iv route is interesting in a therapeutic point of view since it is easily available and it is also tolerogenic. The number of infused cells is compatible with cytopheresis when this will be transposed to Human (see below).

Now, considering the apoptotic cell type, and the apoptotic signal, the analysis of the different studies (Table 3) allows us to identify common requirements: *i*) cells rendered apoptotic are mainly leukocytes at early apoptotic stage (including: mouse spleen cells in 13 studies[2, 14, 84, 85, 105, 109-116], rat PBMC in two studies[117, 118], mouse T cells in two studies[12, 62], human Jurkat T cell line in one[91] and rat or mouse thymocytes in 3 studies[36, 106, 107], while mouse neutrophils [120] and a mouse beta cell line [47] were used in one study, respectively); *ii*) tolerogenic apoptotic stimuli used are the following: γ -irradiation in 10 studies [2, 14, 84, 107, 112, 115-118, 121], UVB irradiation in 7 [47, 85, 91, 108, 109, 113, 114], Fas-mediated death in 3[2, 12, 62], spontaneous apoptosis in culture due to survival factor deprivation in 2[106, 120], and dexamethasone treatment in one study[36]. Few studies compared apoptotic stimuli, but when UVB and γ -irradiation or Fas-mediated apoptosis, UVB-, γ - and X ray-irradiation were compared: no differences were observed[2,

84, 113]. Thus, in order to develop a therapeutic approach, one may propose to use PBMC collected by cytophoresis, expose them to one of the apoptotic signals described above and to control that PBMC are at early stage of apoptosis as attested by Annexin-V staining with limited propidium iodide or 7-AminoActinomycin D (7-AAD) staining.

Finally, analysis of antigen dependency (*i.e.*, whether apoptotic cells should carry the antigen of interest or whether this effect is observed whatever the apoptotic cell origin) is useful to shed light on disease mechanisms and to specify how apoptotic cell infusion interferes with the disease, as well as in a practical point of view to design the future clinical trials. Thus, experimental models can be divided in two concerning antigen dependency (Table 3), with some experimental models requiring apoptotic cells bearing the antigen of interest (*i.e.*, either donor or auto-antigens), such as: diabetes[47], EAE[12, 62, 105], contact hypersensitivity [109-111] or transplantation[85, 112-114]. In contrast, arthritis[36, 106, 107], sepsis[91, 120], fulminant hepatitis [108] and allogeneic hematopoietic cell transplantation [2, 14, 84, 115, 116] are controlled independently of the apoptotic cell origin (Table 3). So, one may speculate that some diseases need tolerance induction against pathogenic auto- or allo-antigens while other implicate a non-specific down-regulation of inflammation or transient immune suppression (Figure 3). In line with this hypothesis, splenic macrophages [14, 120] or liver Kupffer cells [108] have been shown to play a critical role in diseases modulated by the anti-inflammatory effects of apoptotic cell infusion, whereas splenic conventional DC –that are more critical for antigen presentation to T cells than macrophages [29, 51, 52]– are necessary for tolerance to donor allo- or auto-antigens[62, 85, 110, 111, 114]. Some of these studies evaluated functionally the role of APC phagocytosing infused apoptotic cells by *in vivo* depletion using either clodronate loaded liposomes[14, 84], gadolinium chloride[108, 113] or transgenic mice expressing diphtheria toxin receptor under the control of macrophage- or DC-specific promoter rendering macrophages or DC sensitive to diphtheria toxin administration [12, 62, 85]. In addition, *ex vivo* functions of macrophages were also tested after apoptotic cell infusion with reduced secretion of pro-inflammatory cytokine secretion, such as TNF[107] (see also Table 1). Schematically,

inflammatory diseases controlled by apoptotic cell infusion exhibit –after this infusion– a decrease in circulating inflammatory cytokines [107, 120] associated with an increased production of anti-inflammatory cytokines (*i.e.*, IL-10 [36, 106, 108] and/or TGF- β [91, 107, 108]), a modification of macrophage or Kupffer cell function [107, 108, 120] (see also Table 1), and a decrease of neutrophil infiltrates [91, 120]. Neutralization of TGF- β prevents the beneficial effect of apoptotic cell infusion [14, 84, 116]. This confirms that apoptotic cell infusion controls some inflammatory diseases by exerting anti-inflammatory effects. In addition to anti-inflammatory cytokines, pro-angiogenic factors (*e.g.*, VEGF) and metalloproteinases can also be secreted favoring the resolution of inflammation [117, 118]. One may imagine that down-regulation of inflammation by targeting macrophage functions can be sufficient to affect pathogenic T cell or antibody responses, even though apoptotic cells do not interact directly with DC/T cell/B cell crosstalk, as attested by down-regulation of allo- [116] or auto-antibodies [106], or pathogenic Th17 T cells [36]. In contrast, diseases treated with antigen-bearing apoptotic cells (*i.e.*, requiring tolerance to allo- or auto-antigens) involve splenic lymphoid resident conventional DC [62, 85, 114]. These DC dedicated to antigen presentation to T cells may then participate in the induction of regulatory immune cells, including: Tr1 [36, 47, 106, 111], FoxP3⁺Treg [14, 47, 105, 112, 114], regulatory CD8⁺ T cells [109] or regulatory B cells (Breg) [36, 106]. Alternatively, tolerance induction by antigen-bearing apoptotic cell administration may reflect the inhibition of pathogenic Th1 or Th17 cells [12, 36], anti-donor T cells secreting IFN- γ [85, 114], anti-donor allo- [85, 114] or auto-antibodies [47]. Overall, apoptotic cell administration is able to control inflammatory disorders by diminishing the pro-inflammatory state and to induce or restore tolerance to donor allo-antigens or auto-antigens by inhibiting pathogenic T or B cell responses and inducing pro-tolerogenic/regulatory cells (Figure 3).

In a practical point of view, preclinical models are useful to determine antigen dependency as reported in Table 3. Then, if a disease requires a particular antigen, this antigen needs to be expressed by the apoptotic cells, or at least locally present when apoptotic cells are eliminated. This leads to select cells from a particular origin (*e.g.*, the donor in the case of transplantation) or to

engineer patient PBMC to express a nominal antigen as performed in autoimmune diseases[12, 62].

In contrast, if the disease does not need any specific antigen and is treated independently of apoptotic cell origin, PBMC can be obtained from healthy volunteers after written informed consent and a bank of PBMC can be established. Alternatively, PBMC can be obtained from the patient himself. This latter solution is the simplest, even if no lymphopenia, leukemic cells or infections are present.

The cumulative encouraging data obtained in preclinical models allow physicians to initiate clinical studies. This is particularly true for the prevention of acute GvHD. Acute GvHD—an inflammatory disorder associated with allogeneic hematopoietic cell transplantation—is due to the activation of host APC by the conditioning regimen that stimulates donor allogeneic T cells. These activated allogeneic T cells as well as factors released during this process (e.g., TNF) destroy healthy tissues from the recipients including: the liver, the gastro-intestinal tract and the skin[124]. In experimental models (Table 3), infusion of apoptotic cells at time of transplantation induces TGF-beta and increases regulatory T cells that prevent GvHD occurrence [14, 119]. Recently, a phase 1/2a clinical study has been registered in the ClinicalTrials.gov website (<http://clinicaltrials.gov>) under the number, # NCT00524784, and encouraging data have been presented recently in two meetings[125, 126]. In this study, iv donor early apoptotic cell infusion was performed the day before allogeneic hematopoietic cell transplantation in order to prevent acute GvHD occurrence (please see above). Thirteen patients have been treated. Cells were obtained from hematopoietic cell donors after cytopheresis. The cell number has been transposed from animal models and a “dose escalate” has been performed ranging from $35 \times 10^6/\text{kg}$ to $210 \times 10^6/\text{kg}$. No specific toxicities have been associated with iv donor early apoptotic cell infusion. Comparison with historical data concerning acute GvHD occurrence in the same transplantation center or from the literature seems to show a reduction of high grade acute GvHD (grade >II). Interestingly, no severe GvHD was observed in the three patients receiving the highest apoptotic cell number [126]. This clinical study opens the way to apoptotic cell-based therapies in other clinical settings already assessed in experimental models (Table 3).

Conclusion

In conclusion, early apoptotic cell infusion has been reported to treat or prevent experimental inflammatory/autoimmune disorders, as well as complications associated with transplantation (Table 3). A phase 1/2a clinical trial has been performed in 13 patients without specific toxicities and a good early outcome [126]. This confirms the feasibility of such cell-based therapy approach in Humans. Today, the major questions concern: *i*) the interactions of such therapy with other treatments received by patients, as for instance steroids (that increase apoptotic cell removal by macrophages [127, 128]) or methotrexate (that induce macrophage apoptosis [129] and in theory may delay apoptotic cell removal), *ii*) the possible autoimmunity due to delayed or impaired apoptotic cell clearance and *iii*) the potential overall immunosuppression that may alter beneficial immune responses against pathogens for instance, or leukemic cells in the settings of hematopoietic cell transplantation. We have already studied the interactions of apoptotic cell infusion with immunosuppressive drugs routinely used in allogeneic hematopoietic cell transplantation and rapamycin (sirolimus) has a synergic effect [115]. This kind of study has to be extended to other conventional drugs, such as steroids, or methotrexate for RA. Concerning other side effects (autoimmunity or global immunosuppression), careful selection and follow-up of patients may limit these effects. As performed for anti-TNF, patients with active or ongoing infections or a past of cancer should be excluded. In order to prevent autoimmune disease related to impaired apoptotic cell removal, factors known to play a role in this clearance such as C1q have to be analyzed before patient enrolment. Finally, instead of infusing apoptotic cells, apoptotic cell death may be induced *in vivo* using different approaches (*i.e.*, CD3 specific antibody [31]) and tolerance can be achieved with similar mechanisms (for review [119]).

Future perspectives

How the fields described here (*i.e.*, the use of apoptotic cells and the understanding of mechanisms involved in apoptotic cell removal) will evolve in the next 5 to 10 years? We speculate that several phase 1/2a studies and even phase 2 studies, will be performed in different autoimmune diseases or

in the settings of transplantation. Other therapies will be derived from this approach to focus on the main mechanism(s) or factor(s) responsible for the therapeutic effects. For instance, apoptotic cell secretome (that is the factor released by cells undergoing apoptosis) has been shown to exert similar effect on acute myocardial infarction than apoptotic cell infusion [130]. Liposomes expressing phosphatidylserines mimicking an “eat-me” signal associated with anti-inflammatory properties [11, 91] can also be infused in the femoral vein to improve acute myocardial infarction [131]. These two recent publications [130, 131] confirm that the non-specific anti-inflammatory function of apoptotic cell infusion is sufficient to limit acute myocardial infarction. Phosphatidylserine-expressing liposomes are not a cell-based product. This has the advantage of being controlled or produced at large scale using pharmaceutical procedures and not to be dependent on cell therapy regulations. Other perspectives are linked to improvements performed in the understanding of APC subsets and on the characterization of receptors and ligands involved in apoptotic cell removal. One may imagine that the identification of receptor(s) expressed by tolerogenic professional phagocytes would be preferentially targeted to restore tolerance and cure inflammatory auto- or allo-immune diseases.

Executive summary:

Introduction

- Improvement of existing treatment is needed for several inflammatory and/or immune-mediated disorders, including transplantation, acute or chronic inflammatory diseases by modulating the deregulated immune response.

Immunomodulatory properties associated with early apoptotic cells

- Apoptotic cells themselves, elimination of apoptotic cells by innate immune cells or interactions of these cells with apoptotic cells lead to an immunomodulatory microenvironment that may favor or restore tolerance.
- Several factors govern these immunomodulatory properties and mechanisms involved in this process are currently being deciphered.

Preclinical data using early apoptotic cell infusion in experimental models

- Intravenous early apoptotic cell infusion can be used for disease prevention, notably in diseases associated with high mortality/morbidity, for instance, acute graft-*versus*-host disease.
- Intravenous apoptotic cell infusion can be used for disease treatment, such as, sepsis or acute graft rejection.
- Critical aspects to consider to achieve a beneficial therapeutic effect include: *i*) the iv route of administration, but local administration (into the myocardium, lung or peritoneum) is also possible; *ii*) one infusion is often sufficient; *iii*) blood leukocytes is the easiest and major source of apoptotic cells; *iv*) a tolerogenic apoptotic signal inducing early apoptotic cells is required (e.g., γ - or UVB-irradiation).
- The analysis of mechanisms involved in these experimental models suggests that iv apoptotic cell infusion acts by two distinct mechanisms: *i*) modification of the inflammatory microenvironment by targeting professional phagocytes and *ii*) induction of “specific” tolerance to a given antigen through regulatory cell commitment in the favorable microenvironment shaped by the professional phagocytes.

- A phase 1/2a clinical trial performed in the prophylaxis of graft-*versus*-host disease in thirteen patients show no specific side effects at early time point after apoptotic cell infusion. [Note added in proof: the study is now published: Mevorach D et al., Biol Blood Marrow Transplant. 2014 Jan;20(1):58-65.]

References

1. de Carvalho Bittencourt M, Tiberghien P, Saas P: Transplantation of anergic histoincompatible bone marrow cells. *N Engl J Med* 341(14), 1081-1082 (1999).
2. Bittencourt MC, Perruche S, Contassot E *et al.*: Intravenous injection of apoptotic leukocytes enhances bone marrow engraftment across major histocompatibility barriers. *Blood* 98(1), 224-230 (2001).
3. Erwig LP, Henson PM: Immunological consequences of apoptotic cell phagocytosis. *Am J Pathol* 171(1), 2-8 (2007).
4. Newman SL, Henson JE, Henson PM: Phagocytosis of senescent neutrophils by human monocyte-derived macrophages and rabbit inflammatory macrophages. *J Exp Med* 156(2), 430-442 (1982).
5. Ariel A, Serhan CN: New lives given by cell death: macrophage differentiation following their encounter with apoptotic leukocytes during the resolution of inflammation. *Front Immunol* 3, 4 (2012).
6. Savill J, Dransfield I, Gregory C, Haslett C: A blast from the past: clearance of apoptotic cells regulates immune responses. *Nat Rev Immunol* 2(12), 965-975 (2002).
7. Gregory CD, Pound JD: Cell death in the neighbourhood: direct microenvironmental effects of apoptosis in normal and neoplastic tissues. *J Pathol* 223(2), 177-194 (2011).
8. Ochsenbein AF, Kleenerman P, Karrer U *et al.*: Immune surveillance against a solid tumor fails because of immunological ignorance. *Proc Natl Acad Sci U S A* 96(5), 2233-2238 (1999).
9. Kurosaka K, Takahashi M, Watanabe N, Kobayashi Y: Silent cleanup of very early apoptotic cells by macrophages. *J Immunol* 171(9), 4672-4679 (2003).
10. Morimoto K, Amano H, Sonoda F *et al.*: Alveolar macrophages that phagocytose apoptotic neutrophils produce hepatocyte growth factor during bacterial pneumonia in mice. *Am J Respir Cell Mol Biol* 24(5), 608-615 (2001).
11. Fadok VA, Bratton DL, Konowal A, Freed PW, Westcott JY, Henson PM: Macrophages that have ingested apoptotic cells in vitro inhibit proinflammatory cytokine production through

- autocrine/paracrine mechanisms involving TGF-beta, PGE2, and PAF.*J Clin Invest* 101(4), 890-898 (1998).
12. Miyake Y, Asano K, Kaise H, Uemura M, Nakayama M, Tanaka M: Critical role of macrophages in the marginal zone in the suppression of immune responses to apoptotic cell-associated antigens.*J Clin Invest* 117(8), 2268-2278 (2007).
 13. Wermeling F, Chen Y, Pikkarainen T *et al.*: Class A scavenger receptors regulate tolerance against apoptotic cells, and autoantibodies against these receptors are predictive of systemic lupus.*J Exp Med* 204(10), 2259-2265 (2007).
 14. Kleinclaus F, Perruche S, Masson E *et al.*: Intravenous apoptotic spleen cell infusion induces a TGF-beta-dependent regulatory T-cell expansion.*Cell Death Differ* 13(1), 41-52 (2006).
 15. Seitz HM, Camenisch TD, Lemke G, Earp HS, Matsushima GK: Macrophages and dendritic cells use different Axl/Mertk/Tyro3 receptors in clearance of apoptotic cells.*J Immunol* 178(9), 5635-5642 (2007).
 16. Zizzo G, Hilliard BA, Monestier M, Cohen PL: Efficient clearance of early apoptotic cells by human macrophages requires M2c polarization and MerTK induction.*J Immunol* 189(7), 3508-3520 (2012).
 17. Chang GH, Barbaro NM, Pieper RO: Phosphatidylserine-dependent phagocytosis of apoptotic glioma cells by normal human microglia, astrocytes, and glioma cells.*Neuro Oncol* 2(3), 174-183 (2000).
 18. Chan A, Seguin R, Magnus T *et al.*: Phagocytosis of apoptotic inflammatory cells by microglia and its therapeutic implications: termination of CNS autoimmune inflammation and modulation by interferon-beta.*Glia* 43(3), 231-242 (2003).
 19. Takahashi K, Rochford CD, Neumann H: Clearance of apoptotic neurons without inflammation by microglial triggering receptor expressed on myeloid cells-2.*J Exp Med* 201(4), 647-657 (2005).

20. Hughes MM, Field RH, Perry VH, Murray CL, Cunningham C: Microglia in the degenerating brain are capable of phagocytosis of beads and of apoptotic cells, but do not efficiently remove PrPSc, even upon LPS stimulation. *Glia* 58(16), 2017-2030 (2010).
21. Huang FP, Platt N, Wykes M *et al.*: A discrete subpopulation of dendritic cells transports apoptotic intestinal epithelial cells to T cell areas of mesenteric lymph nodes. *J Exp Med* 191(3), 435-444 (2000).
22. Iyoda T, Shimoyama S, Liu K *et al.*: The CD8⁺ dendritic cell subset selectively endocytoses dying cells in culture and in vivo. *J Exp Med* 195(10), 1289-1302 (2002).
23. Morelli AE, Larregina AT, Shufesky WJ *et al.*: Internalization of circulating apoptotic cells by splenic marginal zone dendritic cells: dependence on complement receptors and effect on cytokine production. *Blood* 101(2), 611-620 (2003).
24. Ravichandran KS: Beginnings of a good apoptotic meal: the find-me and eat-me signaling pathways. *Immunity* 35(4), 445-455 (2011).
25. Chung EY, Liu J, Homma Y *et al.*: Interleukin-10 expression in macrophages during phagocytosis of apoptotic cells is mediated by homeodomain proteins Pbx1 and Prep-1. *Immunity* 27(6), 952-964 (2007).
26. Zhang Y, Kim HJ, Yamamoto S, Kang X, Ma X: Regulation of interleukin-10 gene expression in macrophages engulfing apoptotic cells. *J Interferon Cytokine Res* 30(3), 113-122 (2010).
27. De Simone R, Ajmone-Cat MA, Tirassa P, Minghetti L: Apoptotic PC12 cells exposing phosphatidylserine promote the production of anti-inflammatory and neuroprotective molecules by microglial cells. *J Neuropathol Exp Neurol* 62(2), 208-216 (2003).
28. Municio C, Hugo E, Alvarez Y *et al.*: Apoptotic cells enhance IL-10 and reduce IL-23 production in human dendritic cells treated with zymosan. *Mol Immunol* 49(1-2), 97-106 (2011).
29. Segura E, Touzot M, Bohineust A *et al.*: Human inflammatory dendritic cells induce Th17 cell differentiation. *Immunity* 38(2), 336-348 (2013).

30. Voll RE, Herrmann M, Roth EA, Stach C, Kalde J, Girkontaite I: Immunosuppressive effects of apoptotic cells. *Nature* 390(6658), 350-351 (1997).
31. Perruche S, Zhang P, Liu Y, Saas P, Bluestone JA, Chen W: CD3-specific antibody-induced immune tolerance involves transforming growth factor-beta from phagocytes digesting apoptotic T cells. *Nat Med* 14(5), 528-535 (2008).
32. Garabuczi E, Kiss B, Felszeghy S, Tsay GJ, Fesus L, Szondy Z: Retinoids produced by macrophages engulfing apoptotic cells contribute to the appearance of transglutaminase 2 in apoptotic thymocytes. *Amino Acids* 44(1), 235-244 (2013).
33. Williams CA, Harry RA, McLeod JD: Apoptotic cells induce dendritic cell-mediated suppression via interferon-gamma-induced IDO. *Immunology* 124(1), 89-101 (2008).
34. Ravishankar B, Liu H, Shinde R *et al.*: Tolerance to apoptotic cells is regulated by indoleamine 2,3-dioxygenase. *Proc Natl Acad Sci U S A* 109(10), 3909-3914 (2012).
35. Dalli J, Serhan CN: Specific lipid mediator signatures of human phagocytes: microparticles stimulate macrophage efferocytosis and pro-resolving mediators. *Blood* 120(15), e60-72 (2012).
36. Notley CA, Brown MA, Wright GP, Ehrenstein MR: Natural IgM is required for suppression of inflammatory arthritis by apoptotic cells. *J Immunol* 186(8), 4967-4972 (2011).
37. Shibata T, Nagata K, Kobayashi Y: Cutting edge: a critical role of nitric oxide in preventing inflammation upon apoptotic cell clearance. *J Immunol* 179(6), 3407-3411 (2007).
38. Shibata T, Nagata K, Kobayashi Y: A suppressive role of nitric oxide in MIP-2 production by macrophages upon coculturing with apoptotic cells. *J Leukoc Biol* 80(4), 744-752 (2006).
39. Kim S, Elkon KB, Ma X: Transcriptional suppression of interleukin-12 gene expression following phagocytosis of apoptotic cells. *Immunity* 21(5), 643-653 (2004).
40. Stark MA, Huo Y, Burcin TL, Morris MA, Olson TS, Ley K: Phagocytosis of apoptotic neutrophils regulates granulopoiesis via IL-23 and IL-17. *Immunity* 22(3), 285-294 (2005).

41. Stuart LM, Lucas M, Simpson C, Lamb J, Savill J, Lacy-Hulbert A: Inhibitory effects of apoptotic cell ingestion upon endotoxin-driven myeloid dendritic cell maturation.*J Immunol* 168(4), 1627-1635 (2002).
42. Ariel A, Fredman G, Sun YP *et al.*: Apoptotic neutrophils and T cells sequester chemokines during immune response resolution through modulation of CCR5 expression.*Nat Immunol* 7(11), 1209-1216 (2006).
43. Chen W, Frank ME, Jin W, Wahl SM: TGF-beta released by apoptotic T cells contributes to an immunosuppressive milieu.*Immunity* 14(6), 715-725 (2001).
44. Gao Y, Herndon JM, Zhang H, Griffith TS, Ferguson TA: Antiinflammatory effects of CD95 ligand (FasL)-induced apoptosis.*J Exp Med* 188(5), 887-896 (1998).
45. Verbovetski I, Bychkov H, Trahtenberg U *et al.*: Opsonization of apoptotic cells by autologous iC3b facilitates clearance by immature dendritic cells, down-regulates DR and CD86, and up-regulates CC chemokine receptor 7.*J Exp Med* 196(12), 1553-1561 (2002).
46. Ip WK, Lau YL: Distinct maturation of, but not migration between, human monocyte-derived dendritic cells upon ingestion of apoptotic cells of early or late phases.*J Immunol* 173(1), 189-196 (2004).
47. Xia CQ, Peng R, Qiu Y, Annamalai M, Gordon D, Clare-Salzler MJ: Transfusion of apoptotic beta-cells induces immune tolerance to beta-cell antigens and prevents type 1 diabetes in NOD mice.*Diabetes* 56(8), 2116-2123 (2007).
48. Torchinsky MB, Garaude J, Martin AP, Blander JM: Innate immune recognition of infected apoptotic cells directs T(H)17 cell differentiation.*Nature* 458(7234), 78-82 (2009).
49. Bellingan GJ, Caldwell H, Howie SE, Dransfield I, Haslett C: In vivo fate of the inflammatory macrophage during the resolution of inflammation: inflammatory macrophages do not die locally, but emigrate to the draining lymph nodes.*J Immunol* 157(6), 2577-2585 (1996).

50. Schif-Zuck S, Gross N, Assi S, Rostoker R, Serhan CN, Ariel A: Saturated-efferocytosis generates pro-resolving CD11b low macrophages: modulation by resolvins and glucocorticoids.*Eur J Immunol* 41(2), 366-379 (2011).
51. Delamarre L, Pack M, Chang H, Mellman I, Trombetta ES: Differential lysosomal proteolysis in antigen-presenting cells determines antigen fate.*Science* 307(5715), 1630-1634 (2005).
52. Segura E, Durand M, Amigorena S: Similar antigen cross-presentation capacity and phagocytic functions in all freshly isolated human lymphoid organ-resident dendritic cells.*J Exp Med*, (2013).
53. Wynn TA, Chawla A, Pollard JW: Macrophage biology in development, homeostasis and disease.*Nature* 496(7446), 445-455 (2013).
54. Merad M, Sathe P, Helft J, Miller J, Mortha A: The dendritic cell lineage: ontogeny and function of dendritic cells and their subsets in the steady state and the inflamed setting.*Annu Rev Immunol* 31, 563-604 (2013).
55. Xu W, Roos A, Schlagwein N, Woltman AM, Daha MR, van Kooten C: IL-10-producing macrophages preferentially clear early apoptotic cells.*Blood* 107(12), 4930-4937 (2006).
56. Uderhardt S, Herrmann M, Oskolkova OV *et al.*: 12/15-lipoxygenase orchestrates the clearance of apoptotic cells and maintains immunologic tolerance.*Immunity* 36(5), 834-846 (2012).
57. Ravishankar B, Chandler, P, McGaha, T: Early events in immunologic tolerance to apoptotic cells are dependent on marginal zone macrophage CCL22 production. *J Immunol* 190 suppl, Abstract #4081 (2013).
58. Soroosh P, Doherty TA, Duan W *et al.*: Lung-resident tissue macrophages generate Foxp3+ regulatory T cells and promote airway tolerance.*J Exp Med* 210(4), 775-788 (2013).
59. Zigmond E, Jung S: Intestinal macrophages: well educated exceptions from the rule.*Trends Immunol* 34(4), 162-168 (2013).
60. Segura E, Valladeau-Guilemond J, Donnadiou MH, Sastre-Garau X, Soumelis V, Amigorena S: Characterization of resident and migratory dendritic cells in human lymph nodes.*J Exp Med* 209(4), 653-660 (2012).

61. Idoyaga J, Fiorese C, Zbytnuik L *et al.*: Specialized role of migratory dendritic cells in peripheral tolerance induction.*J Clin Invest*, (2013).
62. Qiu CH, Miyake Y, Kaise H, Kitamura H, Ohara O, Tanaka M: Novel subset of CD8{alpha}+ dendritic cells localized in the marginal zone is responsible for tolerance to cell-associated antigens.*J Immunol* 182(7), 4127-4136 (2009).
63. Vitali C, Mingozzi F, Broggi A *et al.*: Migratory, and not lymphoid-resident, dendritic cells maintain peripheral self-tolerance and prevent autoimmunity via induction of iTreg cells.*Blood* 120(6), 1237-1245 (2012).
64. Guillelliams M, Crozat K, Henri S *et al.*: Skin-draining lymph nodes contain dermis-derived CD103(-) dendritic cells that constitutively produce retinoic acid and induce Foxp3(+) regulatory T cells.*Blood* 115(10), 1958-1968 (2010).
65. Mucida D, Pino-Lagos K, Kim G *et al.*: Retinoic acid can directly promote TGF-beta-mediated Foxp3(+) Treg cell conversion of naive T cells.*Immunity* 30(4), 471-472; author reply 472-473 (2009).
66. Yamazaki S, Dudziak D, Heidkamp GF *et al.*: CD8+ CD205+ splenic dendritic cells are specialized to induce Foxp3+ regulatory T cells.*J Immunol* 181(10), 6923-6933 (2008).
67. Desch AN, Randolph GJ, Murphy K *et al.*: CD103+ pulmonary dendritic cells preferentially acquire and present apoptotic cell-associated antigen.*J Exp Med* 208(9), 1789-1797 (2011).
68. Li J, Park J, Foss D, Goldschneider I: Thymus-homing peripheral dendritic cells constitute two of the three major subsets of dendritic cells in the steady-state thymus.*J Exp Med* 206(3), 607-622 (2009).
69. Hadeiba H, Lahl K, Edalati A *et al.*: Plasmacytoid dendritic cells transport peripheral antigens to the thymus to promote central tolerance.*Immunity* 36(3), 438-450 (2012).
70. Parnaik R, Raff MC, Scholes J: Differences between the clearance of apoptotic cells by professional and non-professional phagocytes.*Curr Biol* 10(14), 857-860 (2000).

71. Wagner BJ, Lindau D, Ripper D *et al.*: Phagocytosis of dying tumor cells by human peritoneal mesothelial cells.*J Cell Sci* 124(Pt 10), 1644-1654 (2011).
72. Wood W, Turmaine M, Weber R *et al.*: Mesenchymal cells engulf and clear apoptotic footplate cells in macrophageless PU.1 null mouse embryos.*Development* 127(24), 5245-5252 (2000).
73. Dini L, Lentini A, Diez GD *et al.*: Phagocytosis of apoptotic bodies by liver endothelial cells.*J Cell Sci* 108 (Pt 3), 967-973 (1995).
74. Rock KL, Latz E, Ontiveros F, Kono H: The sterile inflammatory response.*Annu Rev Immunol* 28, 321-342 (2010).
75. Kirsch T, Woywodt A, Beese M *et al.*: Engulfment of apoptotic cells by microvascular endothelial cells induces proinflammatory responses.*Blood* 109(7), 2854-2862 (2007).
76. Tso GH, Law HK, Tu W, Chan GC, Lau YL: Phagocytosis of apoptotic cells modulates mesenchymal stem cells osteogenic differentiation to enhance IL-17 and RANKL expression on CD4+ T cells.*Stem Cells* 28(5), 939-954 (2010).
77. Coles HS, Burne JF, Raff MC: Large-scale normal cell death in the developing rat kidney and its reduction by epidermal growth factor.*Development* 118(3), 777-784 (1993).
78. Ichimura T, Asseldonk EJ, Humphreys BD, Gunaratnam L, Duffield JS, Bonventre JV: Kidney injury molecule-1 is a phosphatidylserine receptor that confers a phagocytic phenotype on epithelial cells.*J Clin Invest* 118(5), 1657-1668 (2008).
79. Reizis B, Bunin A, Ghosh HS, Lewis KL, Sisirak V: Plasmacytoid dendritic cells: recent progress and open questions.*Annu Rev Immunol* 29, 163-183 (2011).
80. Ochando JC, Homma C, Yang Y *et al.*: Alloantigen-presenting plasmacytoid dendritic cells mediate tolerance to vascularized grafts.*Nat Immunol* 7(6), 652-662 (2006).
81. Hoeffel G, Ripoche AC, Matheoud D *et al.*: Antigen crosspresentation by human plasmacytoid dendritic cells.*Immunity* 27(3), 481-492 (2007).

82. Bastos-Amador P, Perez-Cabezas B, Izquierdo-Useros N *et al.*: Capture of cell-derived microvesicles (exosomes and apoptotic bodies) by human plasmacytoid dendritic cells.*J Leukoc Biol* 91(5), 751-758 (2012).
83. Schiller M, Parcina M, Heyder P *et al.*: Induction of type I IFN is a physiological immune reaction to apoptotic cell-derived membrane microparticles.*J Immunol* 189(4), 1747-1756 (2012).
84. Bonnefoy F, Perruche S, Couturier M *et al.*: Plasmacytoid dendritic cells play a major role in apoptotic leukocyte-induced immune modulation.*J Immunol* 186(10), 5696-5705 (2011).
85. Wang Z, Shufesky WJ, Montecalvo A, Divito SJ, Larregina AT, Morelli AE: In situ-targeting of dendritic cells with donor-derived apoptotic cells restrains indirect allorecognition and ameliorates allograft vasculopathy.*PLoS One* 4(3), e4940 (2009).
86. Angelot F, Seilles E, Biichle S *et al.*: Endothelial cell-derived microparticles induce plasmacytoid dendritic cell maturation: potential implications in inflammatory diseases.*Haematologica* 94(11), 1502-1512 (2009).
87. Hanayama R, Tanaka M, Miwa K, Shinohara A, Iwamatsu A, Nagata S: Identification of a factor that links apoptotic cells to phagocytes.*Nature* 417(6885), 182-187 (2002).
88. Ishimoto Y, Ohashi K, Mizuno K, Nakano T: Promotion of the uptake of PS liposomes and apoptotic cells by a product of growth arrest-specific gene, gas6.*J Biochem* 127(3), 411-417 (2000).
89. Galvan MD, Greenlee-Wacker MC, Bohlson SS: C1q and phagocytosis: the perfect complement to a good meal.*J Leukoc Biol* 92(3), 489-497 (2012).
90. Ravichandran KS, Lorenz U: Engulfment of apoptotic cells: signals for a good meal.*Nat Rev Immunol* 7(12), 964-974 (2007).
91. Huynh ML, Fadok VA, Henson PM: Phosphatidylserine-dependent ingestion of apoptotic cells promotes TGF-beta1 secretion and the resolution of inflammation.*J Clin Invest* 109(1), 41-50 (2002).

92. Asano K, Miwa M, Miwa K *et al.*: Masking of phosphatidylserine inhibits apoptotic cell engulfment and induces autoantibody production in mice.*J Exp Med* 200(4), 459-467 (2004).
93. Bondanza A, Zimmermann VS, Rovere-Querini P *et al.*: Inhibition of phosphatidylserine recognition heightens the immunogenicity of irradiated lymphoma cells in vivo.*J Exp Med* 200(9), 1157-1165 (2004).
94. Cohen PL, Caricchio R, Abraham V *et al.*: Delayed apoptotic cell clearance and lupus-like autoimmunity in mice lacking the c-mer membrane tyrosine kinase.*J Exp Med* 196(1), 135-140 (2002).
95. Hanayama R, Nagata S: Impaired involution of mammary glands in the absence of milk fat globule EGF factor 8.*Proc Natl Acad Sci U S A* 102(46), 16886-16891 (2005).
96. Mevorach D, Mascarenhas JO, Gershov D, Elkon KB: Complement-dependent clearance of apoptotic cells by human macrophages.*J Exp Med* 188(12), 2313-2320 (1998).
97. Ogden CA, deCathelineau A, Hoffmann PR *et al.*: C1q and mannose binding lectin engagement of cell surface calreticulin and CD91 initiates macropinocytosis and uptake of apoptotic cells.*J Exp Med* 194(6), 781-795 (2001).
98. Paidassi H, Tacnet-Delorme P, Garlatti V *et al.*: C1q binds phosphatidylserine and likely acts as a multiligand-bridging molecule in apoptotic cell recognition.*J Immunol* 180(4), 2329-2338 (2008).
99. Galvan MD, Foreman DB, Zeng E, Tan JC, Bohlsos SS: Complement component C1q regulates macrophage expression of Mer tyrosine kinase to promote clearance of apoptotic cells.*J Immunol* 188(8), 3716-3723 (2012).
100. Benoit ME, Clarke EV, Morgado P, Fraser DA, Tenner AJ: Complement protein C1q directs macrophage polarization and limits inflammasome activity during the uptake of apoptotic cells.*J Immunol* 188(11), 5682-5693 (2012).
101. Kerr JF, Wyllie AH, Currie AR: Apoptosis: a basic biological phenomenon with wide-ranging implications in tissue kinetics.*Br J Cancer* 26(4), 239-257 (1972).

102. Galluzzi L, Vitale I, Abrams JM *et al.*: Molecular definitions of cell death subroutines: recommendations of the Nomenclature Committee on Cell Death 2012. *Cell Death Differ* 19(1), 107-120 (2012).
103. Green DR, Ferguson T, Zitvogel L, Kroemer G: Immunogenic and tolerogenic cell death. *Nat Rev Immunol* 9(5), 353-363 (2009).
104. Griffith TS, Ferguson TA: Cell death in the maintenance and abrogation of tolerance: the five Ws of dying cells. *Immunity* 35(4), 456-466 (2011).
105. Getts DR, Turley DM, Smith CE *et al.*: Tolerance induced by apoptotic antigen-coupled leukocytes is induced by PD-L1+ and IL-10-producing splenic macrophages and maintained by T regulatory cells. *J Immunol* 187(5), 2405-2417 (2011).
106. Gray M, Miles K, Salter D, Gray D, Savill J: Apoptotic cells protect mice from autoimmune inflammation by the induction of regulatory B cells. *Proc Natl Acad Sci U S A* 104(35), 14080-14085 (2007).
107. Perruche S, Saas P, Chen W: Apoptotic cell-mediated suppression of streptococcal cell wall-induced arthritis is associated with alteration of macrophage function and local regulatory T-cell increase: a potential cell-based therapy? *Arthritis Res Ther* 11(4), R104 (2009).
108. Zhang M, Xu S, Han Y, Cao X: Apoptotic cells attenuate fulminant hepatitis by priming Kupffer cells to produce interleukin-10 through membrane-bound TGF-beta. *Hepatology* 53(1), 306-316 (2011).
109. Griffith TS, Kazama H, VanOosten RL *et al.*: Apoptotic cells induce tolerance by generating helpless CD8+ T cells that produce TRAIL. *J Immunol* 178(5), 2679-2687 (2007).
110. Maeda A, Schwarz A, Bullinger A, Morita A, Peritt D, Schwarz T: Experimental extracorporeal photopheresis inhibits the sensitization and effector phases of contact hypersensitivity via two mechanisms: generation of IL-10 and induction of regulatory T cells. *J Immunol* 181(9), 5956-5962 (2008).

111. Maeda A, Schwarz A, Kernebeck K *et al.*: Intravenous infusion of syngeneic apoptotic cells by photopheresis induces antigen-specific regulatory T cells.*J Immunol* 174(10), 5968-5976 (2005).
112. Mougél F, Bonnefoy F, Kury-Paulin S *et al.*: Intravenous infusion of donor apoptotic leukocytes before transplantation delays allogeneic islet graft rejection through regulatory T cells.*Diabetes Metab* 38(6), 531-537 (2012).
113. Sun E, Gao Y, Chen J *et al.*: Allograft tolerance induced by donor apoptotic lymphocytes requires phagocytosis in the recipient.*Cell Death Differ* 11(12), 1258-1264 (2004).
114. Wang Z, Larregina AT, Shufesky WJ *et al.*: Use of the inhibitory effect of apoptotic cells on dendritic cells for graft survival via T-cell deletion and regulatory T cells.*Am J Transplant* 6(6), 1297-1311 (2006).
115. Bonnefoy F, Masson E, Perruche S *et al.*: Sirolimus enhances the effect of apoptotic cell infusion on hematopoietic engraftment and tolerance induction.*Leukemia* 22(7), 1430-1434 (2008).
116. Perruche S, Kleinclauss F, Bittencourt Mde C, Paris D, Tiberghien P, Saas P: Intravenous infusion of apoptotic cells simultaneously with allogeneic hematopoietic grafts alters anti-donor humoral immune responses.*Am J Transplant* 4(8), 1361-1365 (2004).
117. Ankersmit HJ, Hoetzenecker K, Dietl W *et al.*: Irradiated cultured apoptotic peripheral blood mononuclear cells regenerate infarcted myocardium.*Eur J Clin Invest* 39(6), 445-456 (2009).
118. Lichtenauer M, Mildner M, Baumgartner A *et al.*: Intravenous and intramyocardial injection of apoptotic white blood cell suspensions prevents ventricular remodelling by increasing elastin expression in cardiac scar tissue after myocardial infarction.*Basic Res Cardiol* 106(4), 645-655 (2011).
119. Saas P, Gaugler B, Perruche S: Intravenous apoptotic cell infusion as a cell-based therapy toward improving hematopoietic cell transplantation outcome.*Ann N Y Acad Sci* 1209, 118-126 (2010).

120. Ren Y, Xie Y, Jiang G *et al.*: Apoptotic cells protect mice against lipopolysaccharide-induced shock.*J Immunol* 180(7), 4978-4985 (2008).
121. Hotchkiss RS, Chang KC, Grayson MH *et al.*: Adoptive transfer of apoptotic splenocytes worsens survival, whereas adoptive transfer of necrotic splenocytes improves survival in sepsis.*Proc Natl Acad Sci U S A* 100(11), 6724-6729 (2003).
122. Perruche S, Kleinclauss F, Angonin R *et al.*: A single intravenous infusion of apoptotic cells, an alternative cell-based therapy approach facilitating hematopoietic cell engraftment, does not induce autoimmunity.*J Hematother Stem Cell Res* 12(4), 451-459 (2003).
123. Mebius RE, Kraal G: Structure and function of the spleen.*Nat Rev Immunol* 5(8), 606-616 (2005).
124. Ferrara JL, Levine JE, Reddy P, Holler E: Graft-versus-host disease.*Lancet* 373(9674), 1550-1561 (2009).
125. Mevorach D, Shapira, MY, Zuckerman, T, Zazon, J, Grau, A, Rowe, JM: Early apoptotic cells cellular treatment in allogeneic haematopoietic cell transplantation *Bone Marrow Transplant* 46(Suppl 1), S312-S313 (2011).
126. Mevorach D, Reiner, I, Or, R: Single-infusion of donor early apoptotic cells (ApoCell) as prophylaxis of graft-versus-host disease in myeloablative HLA-matched allogeneic bone marrow transplantation.*Blood* 120(21), 4176 (2013).
127. Liu Y, Cousin JM, Hughes J *et al.*: Glucocorticoids promote nonphlogistic phagocytosis of apoptotic leukocytes.*J Immunol* 162(6), 3639-3646 (1999).
128. McCubbrey AL, Sonstein J, Ames TM, Freeman CM, Curtis JL: Glucocorticoids relieve collectin-driven suppression of apoptotic cell uptake in murine alveolar macrophages through downregulation of SIRPalpha.*J Immunol* 189(1), 112-119 (2012).
129. Lo SZ, Steer JH, Joyce DA: Tumor necrosis factor-alpha promotes survival in methotrexate-exposed macrophages by an NF-kappaB-dependent pathway.*Arthritis Res Ther* 13(1), R24 (2011).

130. Lichtenauer M, Mildner M, Hoetzenecker K *et al.*: Secretome of apoptotic peripheral blood cells (APOSEC) confers cytoprotection to cardiomyocytes and inhibits tissue remodelling after acute myocardial infarction: a preclinical study.*Basic Res Cardiol* 106(6), 1283-1297 (2011).
131. Harel-Adar T, Ben Mordechai T, Amsalem Y, Feinberg MS, Leor J, Cohen S: Modulation of cardiac macrophages by phosphatidylserine-presenting liposomes improves infarct repair.*Proc Natl Acad Sci U S A* 108(5), 1827-1832 (2011).
132. Sokolowski JD, Mandell JW: Phagocytic clearance in neurodegeneration.*Am J Pathol* 178(4), 1416-1428 (2011).
133. MacDonald JM, Beach MG, Porpiglia E, Sheehan AE, Watts RJ, Freeman MR: The Drosophila cell corpse engulfment receptor Draper mediates glial clearance of severed axons.*Neuron* 50(6), 869-881 (2006).
134. Lu Z, Elliott MR, Chen Y *et al.*: Phagocytic activity of neuronal progenitors regulates adult neurogenesis.*Nat Cell Biol* 13(9), 1076-1083 (2011).
135. Perry VH, Henderson Z, Linden R: Postnatal changes in retinal ganglion cell and optic axon populations in the pigmented rat.*J Comp Neurol* 219(3), 356-368 (1983).
136. Hall MO, Prieto AL, Obin MS *et al.*: Outer segment phagocytosis by cultured retinal pigment epithelial cells requires Gas6.*Exp Eye Res* 73(4), 509-520 (2001).
137. Nandrot EF, Kim Y, Brodie SE, Huang X, Sheppard D, Finnemann SC: Loss of synchronized retinal phagocytosis and age-related blindness in mice lacking alphavbeta5 integrin.*J Exp Med* 200(12), 1539-1545 (2004).
138. Monks J, Rosner D, Geske FJ *et al.*: Epithelial cells as phagocytes: apoptotic epithelial cells are engulfed by mammary alveolar epithelial cells and repress inflammatory mediator release.*Cell Death Differ* 12(2), 107-114 (2005).
139. Sandahl M, Hunter DM, Strunk KE, Earp HS, Cook RS: Epithelial cell-directed efferocytosis in the post-partum mammary gland is necessary for tissue homeostasis and future lactation.*BMC Dev Biol* 10, 122 (2010).

140. Golpon HA, Fadok VA, Taraseviciene-Stewart L *et al.*: Life after corpse engulfment: phagocytosis of apoptotic cells leads to VEGF secretion and cell growth.*Faseb J* 18(14), 1716-1718 (2004).
141. Juncadella IJ, Kadl A, Sharma AK *et al.*: Apoptotic cell clearance by bronchial epithelial cells critically influences airway inflammation.*Nature* 493(7433), 547-551 (2012).
142. Hall SE, Savill JS, Henson PM, Haslett C: Apoptotic neutrophils are phagocytosed by fibroblasts with participation of the fibroblast vitronectin receptor and involvement of a mannose/fucose-specific lectin.*J Immunol* 153(7), 3218-3227 (1994).
143. Gaiffe E, Pretet JL, Launay S *et al.*: Apoptotic HPV positive cancer cells exhibit transforming properties.*PLoS One* 7(5), e36766 (2012).
144. Hess KL, Tudor KS, Johnson JD, Osati-Ashtiani F, Askew DS, Cook-Mills JM: Human and murine high endothelial venule cells phagocytose apoptotic leukocytes.*Exp Cell Res* 236(2), 404-411 (1997).
145. Xie R, Gao C, Li W *et al.*: Phagocytosis by macrophages and endothelial cells inhibits procoagulant and fibrinolytic activity of acute promyelocytic leukemia cells.*Blood* 119(10), 2325-2334 (2012).
146. Gao C, Xie R, Li W *et al.*: Endothelial cell phagocytosis of senescent neutrophils decreases procoagulant activity.*Thromb Haemost* 109(6), (2013).
147. Hochreiter-Hufford AE, Lee CS, Kinchen JM *et al.*: Phosphatidylserine receptor BAI1 and apoptotic cells as new promoters of myoblast fusion.*Nature* 497(7448), 263-267 (2013).
148. Caruso RA, Fedele F, Finocchiaro G, Arena G, Venuti A: Neutrophil-tumor cell phagocytosis (cannibalism) in human tumors: an update and literature review.*Exp Oncol* 34(3), 306-311 (2012).
149. Xia CQ, Qiu Y, Peng RH, Lo-Dauer J, Clare-Salzler MJ: Infusion of UVB-treated splenic stromal cells induces suppression of beta cell antigen-specific T cell responses in NOD mice.*J Autoimmun* 30(4), 283-292 (2008).

150. Perruche S, Saas P: L14. Immunomodulatory properties of apoptotic cells.*Presse Med* 42(4 Pt 2), 537-543 (2013).
151. Bournazou I, Pound JD, Duffin R *et al.*: Apoptotic human cells inhibit migration of granulocytes via release of lactoferrin.*J Clin Invest* 119(1), 20-32 (2009).
152. Saas P, Bonnefoy F, Kleinclauss F *et al.*: [Towards the use of intravenous apoptotic leukocyte infusion as a cell-based therapy approach?].*Transfus Clin Biol* 15(3), 98-108 (2008).
153. Schneemann M, Schoeden G: Macrophage biology and immunology: man is not a mouse.*J Leukoc Biol* 81(3), 579; discussion 580 (2007).
154. Fang FC, Nathan CF: Man is not a mouse: reply.*J Leukoc Biol* 81(3), 580 (2007).

Reference annotations

Papers of special note have been highlighted as: * of interest ** of considerable interest

*2. Bittencourt MC, Perruche S, Contassot E et al.: Intravenous injection of apoptotic leukocytes enhances bone marrow engraftment across major histocompatibility barriers. *Blood* 98(1), 224-230 (2001).

This paper is the first manuscript reporting the beneficial use of apoptotic cell infusion in an experimental model of allogeneic hematopoietic cell transplantation.

**11. Fadok VA, Bratton DL, Konowal A, Freed PW, Westcott JY, Henson PM: Macrophages that have ingested apoptotic cells in vitro inhibit proinflammatory cytokine production through autocrine/paracrine mechanisms involving TGF-beta, PGE2, and PAF. *J Clin Invest* 101(4), 890-898 (1998).

This seminal paper is one of the first reporting the immunomodulatory functions of apoptotic cells, *via* TGF- β secretion by macrophages phagocytosing apoptotic cells (see also #30)

**12. Miyake Y, Asano K, Kaise H, Uemura M, Nakayama M, Tanaka M: Critical role of macrophages in the marginal zone in the suppression of immune responses to apoptotic cell-associated antigens. *J Clin Invest* 117(8), 2268-2278 (2007).

This paper is interesting since it extends the use of apoptotic cell infusion in another preclinical model of experimental autoimmune encephalomyelitis, EAE and it identifies also that splenic marginal zone macrophages are critical for the inhibition of immune responses against blood-borne apoptotic cell-associated antigens.

*21. Huang FP, Platt N, Wykes M et al.: A discrete subpopulation of dendritic cells transports apoptotic intestinal epithelial cells to T cell areas of mesenteric lymph nodes. *J Exp Med* 191(3), 435-444 (2000).

This paper describes, in rats, a subset of dendritic cells dedicated to transport continually apoptotic cell-derived antigens from intestine to T cell areas of secondary lymphoid organs.

****30.** Voll RE, Herrmann M, Roth EA, Stach C, Kalden JR, Girkontaite I: Immunosuppressive effects of apoptotic cells. *Nature* 390(6658), 350-351 (1997).

This outstanding paper is the first showing that interactions of apoptotic cells with antigen-presenting cells induce immunosuppressive cytokine secretion (here IL-10) and thus apoptotic cells possess transient immunosuppressive functions (see also #11)

****56.** Uderhardt S, Herrmann M, Oskolkova OV et al.: 12/15-lipoxygenase orchestrates the clearance of apoptotic cells and maintains immunologic tolerance. *Immunity* 36(5), 834-846 (2012).
Beside the new role of 12/15-lipoxygenase, this paper reports that tissue resident macrophages may inhibit/control the recruitment of inflammatory monocyte-derived macrophages and then the engulfment of apoptotic cells by these inflammatory macrophages.

***70.** Parnaik R, Raff MC, Scholes J: Differences between the clearance of apoptotic cells by professional and non-professional phagocytes. *Curr Biol* 10(14), 857-860 (2000).

This paper is one of the first papers reporting the role of *amateur* phagocytes in apoptotic cell removal. In addition, it shows that amateur phagocytes need apoptotic cells in a more advanced stage and that they are less efficient.

***104.** Griffith TS, Ferguson TA: Cell death in the maintenance and abrogation of tolerance: the five Ws of dying cells. *Immunity* 35(4), 456-466 (2011).

This is an interesting and recent review describing how tolerance to apoptotic cell-derived antigens is maintained or broken. The authors use the investigative technique used by some detectives and called the 5 Ws (Who, Where, Why, What and When).

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Tables

Table 1. Early apoptotic cells modulate cytokine/factor synthesis by phagocytes		
Nature of the phagocytes	Cytokines or factors* modulated after apoptotic cell interactions (spontaneously or after cell stimulation**)	Ref.
human monocytes	↑ IL-10, ↓ IL-1β, TNF, IL-12 (variable according to incubation time before LPS stimulation) (LPS)	[30]
human monocyte-derived macrophages	↑ TGF-β, ↑ PGE-2, ↓ TxB2, ↓ LKTC4 (spontaneously) ↑ TGF-β, ↓ GM-CSF, IL-1β, IL-8, IL-10, TNF-α (LPS, TLR4 ligand) ↑ TGF-β, ↓ GM-CSF, IL-10, TNF (zymosan, TLR2 ligand)	[11]
human monocyte-derived macrophages; human macrophage cell line RAW264.7; murine macrophage cell line J774	↓ IL-12 p35mRNA, ↓ IL-12 (IFN-γ + LPS). These effects are independent of IL-10 and TGF-β.	[39]
murine peritoneal macrophages; human monocytes; human monocyte-derived macrophages; human macrophage cell line RAW264.7	↑ IL-10 (spontaneously), but difference exists between the phagocyte tested IL-10 was the sole cytokine studied.	[25]
murine peritoneal macrophages	↑ TGF-β <i>in vitro</i> and <i>ex vivo</i> (<i>in vivo</i> exposure) (spontaneously) TGF-β was the sole cytokine studied.	[91]
murine peritoneal macrophages	↓ TNF <i>ex vivo</i> (spontaneously, <i>in vivo</i> exposure in the setting of SCW-induced arthritis, and after <i>in vitro</i> LPS stimulation)	[107]
murine bone-marrow derived DC or macrophages	↓ IL-23 (LPS); IL-23 was assessed indirectly by a IL-17-dependent bioassay	[40]
murine bone-marrow derived DC or macrophages	↓ IL-12 but not TNF (LPS). These effects are independent of IL-10 and TGF-β.	[41]
human monocyte-derived dendritic cells	↓ IL-23, ↑ IL-10, no effect on IL-12p70 or on PGE-2 (zymosan) no effects (LPS)	[28]
murine immature bone marrow-derived CD8α ⁻ CD11b ⁺ DC	↓ IL-1α, IL-1β, IL-6, IL-12p35, IL-12p40, TNFmRNA & ↓ IL-1α, IL-1β, IL-6, TNF; no effect on TGF-β, IL-1Ra, MIF (spontaneously) ↓ IL-1α, IL-1β, IL-6, IL-12p70, TNF, ↑ TGF-β (LPS) IL-10 was not tested.	[23]
murine spleen DC	<i>in vitro</i> ↑ TGF-β (spontaneously) <i>in vivo</i> ↑ TGF-β requires both macrophages and immature DC	[31]
murine microglial cells	↓ IL-1β associated with apoptotic cells <i>in vivo</i> (other cytokines were not tested)	[20]
rat microglial cells	↑ TGF-β, HGF (spontaneously) ↓ NO, PGE-2, TNF, no effect on IL-10 (LPS)	[27]
<p>* In a given study, only the cytokines or factors affected by apoptotic cell exposure were mentioned after the following symbols: ↑ means increase; ↓ means decrease. However, readers have to consider that if a cytokine/factor is mentioned for an experimental condition but not for the other one, it means that this cytokine/factor is not affected in this particular condition; **the agent used to stimulate phagocytes is given. Abbreviations used: HGF, hepatocyte growth factor; LKTC4, leukotriene C4; TxB2, thromboxane B2;</p>		

Table 2. "Non-professional" phagocytes involved in apoptotic cell removal are potential targets for apoptotic cell-based therapies.

Cells involved in removal	Comments	Ref.
normal astrocytes	<i>in vitro</i> ; phosphatidylserine-dependent for review	[17] [132]
glioma cells (tumoralastrocytes)	<i>in vitro</i> ; phosphatidylserine-dependent	[17]
CNS glial cells	<i>in Drosophila</i>	[133]
neuronal progenitors	<i>in vivo</i> ; ELMO1/Rac1-dependent	[134]
neurons	for review	[132]
retina cells	<i>in vivo</i> ; during development	[135]
retinal pigment epithelial cells*	<i>in vivo</i> ; Mertk-dependent	[15]
	Gas6-dependent	[136]
	$\alpha v/\beta 5$ integrin-dependent	[137]
	these 3 pathways implicate phosphatidylserines	
lens epithelial cells	<i>in vitro</i> ; apoptotic cell removal is delayed compared with professional phagocytes and requires late apoptotic cells	[70]
kidney parenchymal cells	<i>in vivo</i> ; during development	[77]
baby hamster kidney cells	<i>in vitro</i> ; apoptotic cell removal is delayed compared with professional phagocytes and requires late apoptotic cells	[70]
kidney tubular epithelial cells	<i>in vivo</i> and <i>in vitro</i> ; <i>Kim-1-dependent</i>	[78]
mammary epithelial cells	<i>in vitro</i> and <i>in vivo</i> ; CD36-, vitronectin receptor $\alpha v/\beta 3$ -, CD91-dependent; associated with TGF- β release	[138]
	<i>in vivo</i> ; MFG-E8-dependent; if altered, local inflammation	[95]
	Mertk-dependent; if altered, local inflammation	[139]
	VEGF secretion after apoptotic cell uptake	[140]
cell line HC11		
lung epithelial cells	<i>in vivo</i> ; Rac-1-dependent; associated with IL-10 secretion; if altered, IL-33 production and local inflammation as well as exacerbation of the Th2 response to allergens	[141]
fibroblasts	vitronectin receptor $\alpha v/\beta 3$ -, mannose/fucose specific lectin-dependent	[142]
	leads to malignant transformation via oncogene transfer	[143]
endothelial cells:	carbohydrate-specific receptor-dependent; increased removal	
Liver	by IL-1 β	[73]
HEV	<i>in vivo</i> ; <i>in vitro</i>	[144]
microvascular HMEC-1 and HUVEC	<i>in vitro</i> ; increase of <i>IL-8</i> and <i>MCP-1/CCL2</i> mRNA as well as IL-8 secretion; enhanced binding of leukocytes to phagocytosing endothelial cells	[75]
HUVEC	MFG-E8-dependent	[145, 146]
peritoneal mesothelial cells	limited to subcellular fragments, slow kinetics	[71]
mesenchymal stem cells (MSC)	<i>in vivo</i> in macrophage-less mice; slow kinetics enhanced MSC osteogenic differentiation; increase of CXCR4 and CXCR5 expression, IL-8, CCL2 and CCL5 secretion, as well as Th17 differentiation (via IL-6)	[72] [76]
skeletal myoblasts	<i>in vitro</i> ; <i>BAI-1-dependent</i>	[147]
tumor cells (gastric carcinoma, glioma)	for a recent review, please see Ref. [148]	[17, 148]
*according to Ref. [3]: "Retinal pigment epithelial cells phagocytose more material over a lifetime than any other cell in the body." Abbreviations : CNS, central nervous system; HEV, high endothelial venule cells; HUVEC, human umbilical vein endothelial cells; Mertk, Mer tyrosine kinase; VEGF, vascular endothelial growth factor.		

Table 3. Potential therapeutic use of apoptotic cell infusion based on experimental models		
Pathologies	Effects, route of administration, cell type and apoptotic stimulus, mechanism(s), models	Ref.
Chronic inflammatory autoimmune diseases		
Type I diabetes	- Prevention; iv; UVB-induced apoptotic beta cell line, NT1 (10^5 weekly, 3 weeks); induction of Th2 response, IL-10-producing Tr1 cells and FoxP3 ⁺ Treg in the spleen; suppression of anti-beta cell auto-Abs; NOD mice - Same effect with UVB-induced apoptotic splenic stroma cells	[47] [149]
Experimental Autoimmune Encephalomyelitis (EAE)	- Prevention; iv; Fas ligand-induced apoptotic T cells (2×10^7); Ag-specific; implication of splenic marginal zone macrophages; diminution of MOG-specific Th1 and Th17 in the spleen; MOG ₃₅₋₅₅ -induced EAE (C57BL/6) - Prevention; iv, Fas ligand-induced apoptotic T cells (2×10^7); Ag-specific; implication of splenic CD8 α^+ CD103 ⁺ CD207 (langerin) ⁺ conventional DC; MOG ₃₅₋₅₅ -induced EAE (C57BL/6) - Prevention; iv but not after sc or ip; apoptotic spleen cells (5×10^7); Ag-specific; implication of IL-10 producing splenic marginal zone PD-L1 ⁺ macrophages; long term maintenance by splenic Treg; B cells are not required; MOG ₃₅₋₅₅ -induced EAE (C57BL/6) or PLP ₁₇₈₋₁₉₁ -induced EAE (SJL)	[12] [62] [105]*
Arthritis	- Prevention; iv (but same data ip); spontaneous apoptotic thymocytes (2×10^7 in total, 3 consecutive days); protection mediated by IL-10 produced by both B and T cells; reduction of pathogenic anti-collagen II auto-Abs; collagen induced arthritis in DBA/1 mice but not in a passive antibody transfer model of arthritis in K/BxN mice - Prevention; ip with SCW immunization; 15 Gray γ -irradiated thymocytes (2×10^8); TGF- β increase; decrease of macrophage pro-inflammatory response (TNF, IFN- γ); increase of blood and draining lymph node Treg; SCW-induced arthritis in Lewis rats - After immunization; iv; dexamethasone or etoposide-induced apoptotic thymocytes (3×10^7 , 3 consecutive days); decrease of draining lymph node Th17 cells; increase of IL-10 producing splenic marginal zone B cells and of IL-10 producing T cells in the draining lymph node; natural IgM-dependent clearance; methylated BSA-induced arthritis in C57BL/6 mice	[106] [107] [36]
Acute inflammatory diseases		
Sepsis	- Resolution of acute inflammation; ip (4×10^7 , day 3) or endotracheal instillation ($1.8-2 \times 10^7$, 36-48 h after); UVB-induced apoptotic human Jurkat T cell line; phosphatidylserine-induced TGF- β secretion; decrease of immunecell infiltrate; thioglycollate-stimulated peritoneum or LPS-stimulated lung - Increase of mice survival (day 0, or 1h, 3 h, 6 or 24 h after); iv; spontaneous apoptotic neutrophils (10^7); reduction of circulating inflammatory cytokines (IL-12, TNF, IFN- γ); decrease of neutrophil infiltration in target organs; reduction of serum LPS levels; implication of macrophage phagocytosis; LPS-induced endotoxic shock in C57BL/6 mice and cecal ligation and puncture sepsis model in C57BL/6 mice - Worsen mice survival (day -5); iv; 10 Gy γ -irradiated spleen cells (5×10^7); lack of IFN- γ production (which is protective); cecal ligation and puncture sepsis model in C57BL/6 mice	[91] [120] [121]
Fulminant hepatitis	- Prevention; iv (day-3 to day-7); UVB-induced apoptotic spleen cells (1.5×10^7 , 2×10^8 no effect); whatever the origin of apoptotic cells; dependent on Kupffer cells and IL-10 via membrane bound TGF- β ; but not on CD25 ⁺ cells or CD11c ⁺ cells; reduction of NO and TNF <i>in vitro</i> ; LPS plus D-galactosamine-induced fulminant hepatitis in C57BL/6 or BALB/c mice	[108]
Contact hypersensitivity	- Prevention (day -7); iv; 3 Gy γ -induced apoptotic spleen cells (1×10^7); Ag-specific; Induction of regulatory TRAIL ⁺ CD8 ⁺ T cells without activating CD4 ⁺ T cell help; delayed-type hypersensitivity using 2,4,6 trinitrobenzene sulfonic acid (TNBS)	[109]

	- Prevention; iv; UVA-irradiated and 8-methoxypsoralen (8-MP)-sensitized spleen cells**This induces apoptosis, but other changes specific to UVA and 8-MP may also occur. (5×10^7); Ag-specific; IL-10 dependent; dependent on CD11c ⁺ DC; contact hypersensitivity using dinitrofluorobenzene	[110, 111]
Transplantation		
Cardiac allograft		
Acute rejection	- Prevention (day-7 before Tx); iv; UVB- or 1.50 Gy-irradiated apoptotic spleen cells (5×10^7); donor-specific; requirement of phagocytosis (host macrophages) and phosphatidylserine recognition; different donor/recipient rat strain combination - Treatment (day 7 after Tx); iv; UVB-induced apoptotic spleen cells (10^7); donor-specific; splenic host CD8 α^+ DC; Intra-graft TGF- β and IL-10 mRNA; Foxp3 ⁺ Treg present in the graft; suppression of systemic anti-donor allo-antibody response and IFN- γ ; different donor/recipient mouse strain combination	[113] [114]
Chronic rejection	- Prevention (day-7); iv; UVB-induced apoptotic spleen cells (10^7); donor-specific; splenic host CD11 ^{high} DC; suppression of systemic anti-donor allo-antibody response and IFN- γ ; presentation of donor apoptotic cell-derived allopeptides declines 3 days after apoptotic cell infusion; intra-abdominal aortic transplantation (BALB/c into C57BL/6 mice)	[85]
Islet allograft	- Prevention (day -7); iv; 35 Gy- γ -irradiated-apoptotic spleen cells (5×10^6); donor-specific; possible involvement of Treg	[112]
Hematopoietic cell transplantation		
Hematopoietic engraftment	- Prevention (day 0, the day of Tx); iv; 40 Gy-irradiated, UVB- or FasAb-induced apoptotic spleen cells (5×10^6); whatever the origin of apoptotic cells (donor, recipient, third party or xenogeneic [human]); different donor/recipient mouse strain combination - This graft facilitating effect is TGF- β -dependent - This effect implicates host splenic macrophages –but not conventional DC; increase of Treg in the spleen - This effect implicates also donor bone marrow-derived PDC that induces Treg commitment via TGF- β ; same effect with X ray-irradiated apoptotic spleen cells	[2] [116] [14] [84]
Acute GvHD	- Prevention (day 0); iv; 40 Gy γ -irradiated donor apoptotic spleen cells (5×10^6); involvement of CD25 ⁺ cells	[14]
Chronic GvHD	- Treatment (week 6 after Tx); iv; X-ray-irradiated apoptotic spleen cells (5×10^6); DBA2 into B6D2F1 model	***
Allo-Ab after graft rejection	- Prevention (day 0); iv; 40 Gy-irradiated apoptotic spleen cells (5×10^6); whatever the origin of apoptotic cells; TGF- β -dependent; same model as in [2, 14]	[116]
Acute myocardial infarction	- Prevention (onset of ischemia); iv; 45 Gy γ -irradiated apoptotic PBMC (8×10^6); Attenuation of infarcted size and improvement of functional parameters assessed by echography; increased homing of endothelial progenitors; increase of IL-8, VEGF and MMP9 mRNA <i>in vitro</i> ; ligation the left anterior descending artery in rat - The same effect is observed after intramyocardial injection; increase of CD68 ⁺ cell infiltrate	[117] [118]
*The target antigen is coupled with syngeneic splenocytes using ethylene carbodiimide (ECDI). ECDI induces splenocyte apoptosis. ** This induces apoptosis but other changes specific to ECDI may also occur; ***our unpublished data. Abbreviations: Abs, antibodies; Ag, antigen; GvHD, graft-versus host disease; ip, intraperitoneal; iv, intravenous infusion; LPS, lipopolysaccharide; MOG ₃₅₋₅₅ , myelin oligodendrocyte glycoprotein peptide; NO, nitric oxide; OVA, ovalbumine peptide; PBMC, peripheral blood mononuclear cells; PLP, proteolipid protein; sc, subcutaneous; SCW, streptococcal cell wall; Tx, transplantation; UV, ultraviolet; This table was updated and adapted from Ref. [119, 150].		

Figure legends:

Figure 1. Signals involved in apoptotic cell removal. Different signals orchestrate apoptotic cell removal by neighbor cells (*amateur* phagocytes, see Table 1) or professional phagocytes, such as macrophages or conventional DC (cDC). These signals include: (1) the loss of “do not eat-me” signals; (2) the secretion of “find-me” signals that can be counterbalanced by “keep out” signals[151]; (3) the acquisition of “eat-me” signals. Soluble factors can participate to acceleratedelimination of apoptotic cells. Adapted from Ref. [150]. Abbreviations used:BAI-1, brain angiogenesis inhibitor-1;CRP, C reactive protein; CRT, calreticulin; C1q, complement component C1q; Gas6, Growth Arrest-specific 6; KIM-1, kidney injury molecule-1 (also known as TIM-1); MBL, mannose-binding lectin; Mertk, Mer tyrosine kinase; MFG-E8, milk fat globule EGF 8 protein called also lactadherin; PS, phosphatidylserines; SP-A, pulmonary surfactant A; SP-D, pulmonary surfactant D; TSP1, thrombospondin-1.

Figure 2.Immunomodulatory microenvironment created by apoptotic cells.During the apoptotic process, apoptotic cells can produce spontaneously anti-inflammatory factors, such as IL-10[44] or TGF- β [43], or be a source of CCR5 chemokine receptor that neutralizes its ligands, CCL3/MIP-1 α or CCL5/RANTES and subsequently blocks immune cell migration[42]. Apoptotic cells interact with several innate immune cellsor antigen-presenting cells (APC), including: monocytes, macrophages (M Φ), microglia in the brain, conventional dendritic cells (cDC), NK cells or B cells. Uptake of apoptotic cells or only the interaction with apoptotic cells lead to modulation of several factors in innate cells or APC. These factors are mentioned in boxes linked to each APC or innate cell subset. Adapted from Ref. [152]. Some of these factors are produced spontaneously after apoptotic cell encounter or increased or diminished after a subsequent stimulation by TLR ligands in the context of inflammation (see Table 1). *Concerning NO synthesis, differences existbetween human and muse macrophages [153] and maybe also between *in vivo* and *in vitro* conditions[154]. Abbreviations used: AhR, aryl hydrocarbon receptor; GM-CSF, granulocyte and macrophage colony stimulating factor;

HGF, hepatocyte growth factor; IL, interleukin; IL-1RA, interleukin-1 receptor antagonist; iNOS, inducible nitric oxide synthase; LT4C, leukotriene C4; NGF, nerve growth factor; NO, nitric oxide; NOS2, nitric oxide synthase-2; PAF, platelet-activating factor; PGE-2, prostaglandin-E2, RvE, resolvin E; TXA2, thromboxane A2; VEGF, vascular endothelial growth factor A. ↓, decrease; ↑, increase; see also text.

Figure 3. Anti-inflammatory effects *versus* tolerance induction after early apoptotic cell infusion.

Apoptotic cell-induced immunosuppression is transient (limited to the time course of apoptotic cell removal and the persistence of immunosuppressive cytokines: mainly IL-10 and TGF- β , see also Figure 2), localized to the site where the cells are dying and/or being eliminated (*i.e.*, the spleen after iv infusion), and non-specific (*i.e.*, all the cells sensitive to immunosuppressive cytokines at the site of apoptotic cell removal are affected). Experimental models of pathological disorders have been shown to respond to this anti-inflammatory effect, including arthritis, sepsis, fulminant hepatitis, allogeneic hematopoietic cell engraftment, or acute myocardial infarction (see text). In contrast, apoptotic cell-induced tolerance is related to antigen (Ag)-specific regulatory cell induction. This antigen-specific tolerance may persist (according to the life span of the induced pTreg) and may not be restricted to the site of apoptotic cell clearance (depending on the migratory properties of the generated pTreg). Experimental models of pathological diseases, such as: type 1 diabetes, EAE, contact hypersensitivity, prevention or treatment of acute graft rejection, prevention of chronic graft rejection or of acute GvHD (aGvHD) have been shown to require infusion of apoptotic cells bearing specific auto- or donor allo-antigen(s). After iv infusion, splenic macrophages are rather involved in anti-inflammatory effect of apoptotic cells, whereas splenic lymphoid resident conventional DC are implicated in tolerance induction.